

THERMOREGULATION IN INTENSIVELY LACTATING COWS IN NEAR-NATURAL CONDITIONS

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SUMMARY

1. Thermoregulatory reactions of lactating cows (33 kg milk/day) have been measured in summer (25–39° C) and in winter (9·5–24° C) at 3 hr intervals, during four nychthemeral (24 hr) cycles in each season.

2. The rectal-to-tympanic temperature gradient increased with rising body temperatures. The seasonal changes were larger for the rectal temperatures than for the tympanic membrane temperatures. These and the significantly lower correlations between rectal temperatures and regulatory responses suggest that in the ruminant rectal temperatures are considerably affected by rumen metabolism and do not represent a reliable index of the regulated temperature.

3. In the winter the regulatory responses were correlated with skin temperatures only. In the summer responses were correlated with both skin and tympanic temperatures, excepting for skin water loss.

4. The seasonal difference in the effects of skin and tympanic temperatures on regulatory responses was associated with a small change in mean tympanic temperature. The twofold larger nychthemeral fluctuation in the summer tympanic temperature is suggested to cause the seasonal difference in the thermoregulatory mode.

5. The winter range of nychthemeral fluctuations in tympanic temperature suggests a range of permitted core thermolability. A wider permitted core thermolability in summer is unlikely to be a mechanism of acclimatization in the cow.

INTRODUCTION

The operative characteristics of thermoregulation have been studied mostly in artificially created climates and in animals which had limited experience of the cycling outdoor climate (Hammel, 1968). These studies generally demonstrated the ability of the animals to maintain body-core temperature within a narrow range whenever the imposed ambient conditions were not excessive.

Large nycthemeral variations in deep body temperature were, however, found in mammals exposed to warm climates (Schmidt-Nielsen, Schmidt-Nielsen, Jarnum & Houpt, 1957; Berman, 1968; Bligh & Harthoorn, 1965). These cycles may reflect a limited capacity to maintain homoeothermy, or alternatively may represent an economy of thermoregulatory effort. The nature of this thermolability is not clear.

A study of the thermoregulatory compensatory reactions accompanying the cycles in body temperature may throw light on the mechanism underlying these cycles. The pattern of the compensatory reactions would indicate whether this core thermolability is permitted or is due to inadequate compensations.

This paper reports a study of thermoregulatory reactions of high-yielding dairy cattle in a hot dry desert. The combined effects of the heat increment of milk synthesis and external heat load were expected to impose severe thermal stress on the animals.

METHODS

This study was carried out in the desert area south of the Dead Sea. Air temperature ranges from a mean minimum of 5° C in winter to a mean maximum of 43° C in the summer. Observations of thermoregulatory reactions were performed every 3 hr during four consecutive nycthemeral cycles in mid-summer and in mid-winter.

Animals. The experiments were carried out on four Israeli-Holstein adult dairy cows in good health. The animals were stanchioned in an open-sided shelter; they were protected from direct solar radiation. These animals were 1-2 months *post partum* and were yielding 30-35 kg milk per day. Experimental procedure did not depress milk yield. Mean body weight (of all four animals) was 600 kg. The observations were carried out on one group of animals in the summer and on another group in the winter. The two groups were of similar age, body weight, stage of lactation and milk yield.

Temperature measurements. All temperature measurements were potentiometric and carried out using 38 s.w.g. copper-constantan, enamelled and polyethylene-coated thermocouples. The reference junctions were embedded in modelling clay and set in a Perspex cylinder immersed in a 14 l. capacity circulated water-bath. The water temperature in the bath was stable to within $\pm 0.02^\circ$ C.

It has been shown that the black-globe temperature is a satisfactory single criterion of the environmental heat load (Woodcock, Pratt & Breckenridge, 1960). It was used throughout these trials as the parameter of climate to which thermal states were related.

Skin temperature was measured on small shaven patches on the back over the sacrum and thorax, mid-flank, lateral abdomen, hind leg and both ears. The bare ends of the thermocouple wires were attached to the skin for a length of 3 cm with contact cement. Rectal temperatures were measured at a depth of 15 cm.

For the tympanic membrane temperature measurements the lead wires were inserted into a 15 cm long polyvinylchloride tube. The wires were separated and threaded through a polyethylene catheter (1.0 mm external diameter) so that the measuring junction was set at the end of the terminal loop. The probe was inserted slowly into the *meatus* until the animal reacted to the contact of the loop on the

eardrum. The polyvinylchloride tube was then fixed on the inner surface of the external ear using contact cement and a strip of elastic bandage. While fixing the probe, the ear was held pointing upwards and backwards. This maintained a permanent contact of the loop end on the ear drum. After the initial excitement, the animals did not show any signs of discomfort and reacted normally.

Skin non-evaporative heat loss. Hatfield-type heat-flow disks (Joyce, Loeb and Co., Gateshead, U.K.) were used to determine non-evaporative heat loss. They were attached to the shaven skin using contact cement. The measuring sites were the back over the sacrum and thorax, lateral abdomen and both ears.

The e.m.f. outputs from the rectal and tympanic probes and from the heat-flow disks were amplified using a d.c. chopper amplifier (Dana Laboratories Inc., Irvine, Calif.) and read to $0.5 \mu\text{V}$. The e.m.f. outputs from the skin thermocouples were recorded on a potentiometric recorder (Westronics Inc., Fort Worth, Texas).

Skin evaporative heat loss. A ventilated capsule similar to that used by Tennenbaum & Volcani (1962) was used to measure skin water-vapour loss. The sampled area was 25 cm^2 . The concentration of the water vapour was sensed by narrow-range sensors (Hygrodynamids, Inc., Silver Spring, Maryland) at the inlet and the outlet of the ventilated capsule. The difference in temperature between the ingoing and the outgoing air did not exceed 1°C at ambient temperatures below 25°C and was not measurable at ambient temperatures above 32°C . The water-vapour losses from the skin were measured on both flanks. In one animal water-vapour loss was measured on ten sites. Their mean served to correct the flank data to represent the whole body surface.

Respiratory frequency. Flank respiratory movements only were counted twice over 30 sec periods to give an estimate of respiratory frequency.

Measuring procedure. High-producing animals need considerable time to consume their feed, ruminating and lying at rest. Preliminary work showed that the animals are not disturbed by short (15 min) sessions of measurements carried out every 3 hr. The animals were machine-milked in the stalls. Feed and water were offered *ad libitum*. The cows were accustomed to handling and no adverse reactions were observed during the experiment.

RESULTS

Rectal temperature. Rectal temperatures were not dependent upon black-globe temperatures (T_g) in the range 9°C to about 28°C (Fig. 1). The rectal temperatures were significantly affected at the highest T_g during the summer ($r = 0.479$, $b = 0.04$, $P < 0.05$).

This difference between the low and high temperature ranges is not likely to be due to the observations being performed on different animals in the two seasons, as the data of the two groups intermixed in the overlapping ambient temperatures. This was true also for the other parameters investigated in this experiment.

The ratio of the nycthemeral change in T_g to the respective change in rectal temperatures can serve as an index of thermostability. This ratio was 0.024 in the winter period and 0.082 in the summer period, although the nycthemeral fluctuation in T_g was very similar in the two seasons (Table 1).

Tympanic membrane temperature. The tympanic membrane tempera-

tures showed a similar relationship to T_g as did rectal temperatures (Fig. 2). At the higher ambient temperatures tympanic temperature increased with T_g ($r = 0.466$, $b = 0.03$, $P < 0.05$). The ratio of the nycthemeral change in tympanic temperature to that in T_g was 0.026 in the winter period and 0.055 in the summer period.

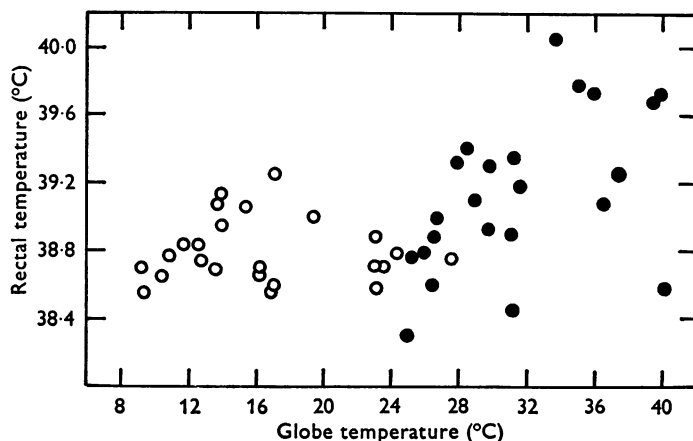


Fig. 1. Scatter of group means of rectal temperature plotted *versus* ambient globe temperature at each measurement period in the two seasons. ○, Winter data; ●, summer data.

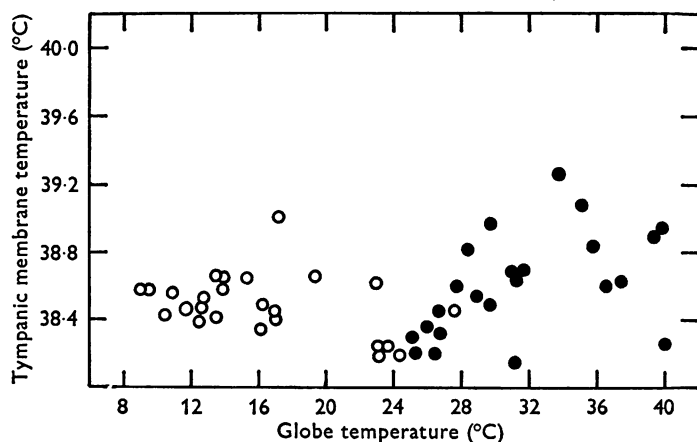


Fig. 2. Scatter of group means of tympanic membrane temperature plotted *versus* ambient globe temperature at each measurement period in the two seasons. ○, Winter data; ●, summer data.

Skin temperatures. The mean of the trunk skin temperatures was used as an index of main body skin temperatures. The correlations of mean skin temperature with T_g were statistically highly significant in both seasons (Fig. 3). The r values in winter and summer were 0.47 and 0.89,

TABLE 1. Means and s.d. of thermoregulatory responses in the two seasons

	Rectal temp. (° C)	Tympanic temp. (° C)	Mean skin temp. (° C)	Ear- skin temp. (° C)	Skin heat loss*	Skin water loss†	K_{ra} ‡	Resp. freq. (min ⁻¹)	Black globe temp. (° C)
Means	39.16 ± 0.43	38.61 ± 0.31	36.2 ± 1.4	36.6 ± 1.3	79 ± 43	159 ± 100	63.3 ± 32	71 ± 14	31.8 ± 4.9
Mean 24 hr fluctuation	± 0.57	± 0.38	± 2.0	± 1.9	± 63	± 81	± 20	± 17	± 7.0
Means	38.79 ± 0.19	38.50 ± 0.18	33.8 ± 1.6	34.4 ± 1.7	183 ± 52	108 ± 69	55.0 ± 18	41 ± 13	16.8 ± 5.6
Mean 24 hr fluctuation	± 0.17	± 0.19	± 1.6	± 1.5	± 66	± 85	± 18	± 18	± 7.3

* Non-evaporative heat loss as kcal/hr.m².† g/hr.m².‡ Rectal-to-skin heat conductance as kcal/hr.m². ° C.

respectively. The effect of T_g on mean skin temperature was larger in the summer period; the respective coefficients of regression were 0.27 in the summer and 0.17 in the winter ($P > 0.01$). No abrupt change in the rate of increase of T_s with rising T_g was evident in either range of ambient temperatures.

Ear temperatures were strongly correlated with mean skin temperature ($r = 0.912$) and were of same magnitude as the latter in both seasons. This suggests a similar vasomotor state in the tissues underlying these surfaces.

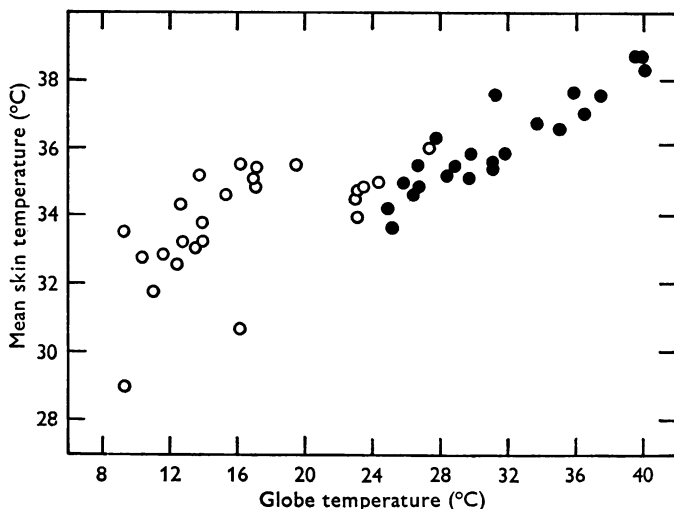


Fig. 3. Scatter of group means of average skin temperature plotted *versus* ambient globe temperature at each measurement period in the two seasons. ○, Winter data; ●, summer data.

Sweating. Skin water-vapour loss was generally steady; there were, however, fluctuations, during which sweating rates decreased to about 65 % of the steady rates. These fluctuations were irregular and were observed only during the warmer part of the day. These fluctuations recall the patterns of sweating reported by Allen & Bligh (1969). Forthwith all data on sweating are derived from the steady rate phases only. These were of very similar intensity on both sides ($r = 0.885$).

Sweating rates were correlated with mean skin temperature in both seasons ($r = 0.63$, $P < 0.01$). Within the range of ambient conditions in this experiment the relationship of sweating rate to mean skin temperature was linear (Fig. 4). There was no evidence for a threshold skin temperature at which sweating was initiated. The lowest rates of sweating were in the 30–50 g/m².hr range; the highest mean sweating rate, recorded in the summer, was 422 g/m².hr. The mean rate of increase in the sweating rate

with rising mean skin temperature was $75 \text{ g/m}^2 \cdot \text{hr per } ^\circ \text{C}$. The regressions of sweating rate on skin temperature did not differ in the two seasons.

Heat production. Total skin heat loss was obtained by combining non-evaporative and evaporative heat losses from the skin. This value was then added to the estimated respiratory heat loss, calculated from data on similar animals under similar ambient heat loads (Kibler & Brody, 1952). The derived data were corrected for changes in body heat content (Hardy & DuBois, 1938). This yielded an estimate of total heat production.

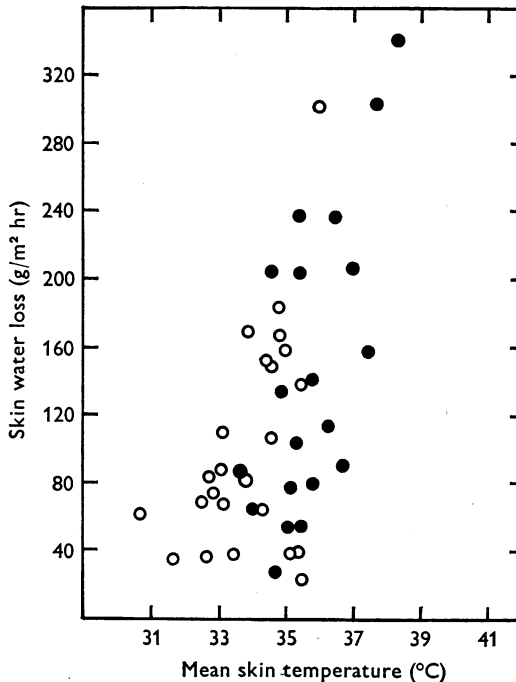


Fig. 4. Scatter of group means of skin water loss plotted *versus* mean skin temperature at each measurement period in the two seasons. Legend as in Fig. 1.

Heat production was not correlated with T_g within the nycthemeral cycle in either season. No particular trend of change in heat production could be discerned in the nycthemeral cycle. Heat production was by 24% higher in the winter time than in the summer. It was negatively correlated with tympanic temperature in the summer ($r = 0.471$, $P < 0.05$).

Body-heat conductance. The relationship of rectal-to-skin heat conductance (K_{rs}) to the parameters of body thermal state may serve as an index of the thermal strain as sensed by the regulatory system. A highly significant relationship between mean skin temperature and K_{rs} was found

in both seasons ($r = 0.73$, $P < 0.01$). The pattern and the actual K_{rs} values were very similar for both the rectal-to-trunk and the rectal-to-ear conductance data.

The results were characterized by the absence of any effect of mean skin temperature on K_{rs} up to a certain threshold level (Fig. 5); above it a

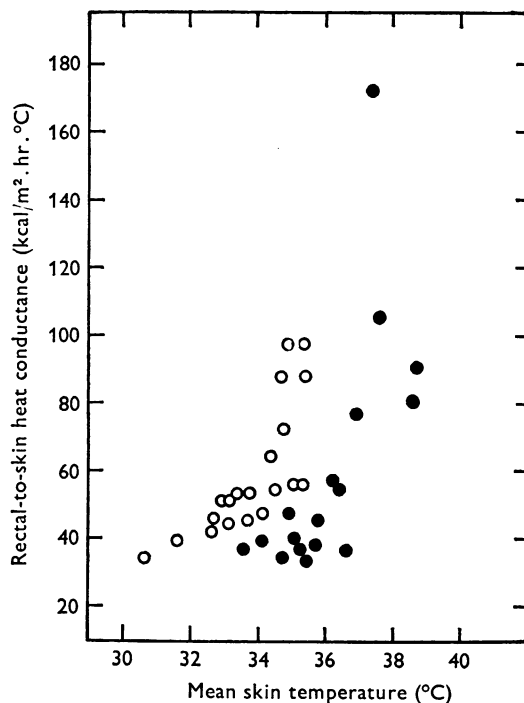


Fig. 5. Scatter of group means of rectal-to-skin heat conductance plotted *versus* mean skin temperature at each measurement period in the two seasons. Legend as in Fig. 1.

steep increase in K_{rs} occurred from a base line of 40–50 kcal/m² . hr. °C to about 80–90 kcal/m² . hr. °C over a skin-temperature increment of about 1° C.

The threshold skin temperature differed in the two seasons. In the summer the inflexion in K_{rs} occurred at a skin temperature of about 37° C and in the winter at about 35° C.

Relationship of rectal to tympanic temperatures. These two parameters of body core temperature were strongly correlated (Fig. 6). The pooled r value was 0.863 ($P < 0.01$). Of the two, the tympanic temperature was the more stable. It showed smaller fluctuations in the summer nycthemeral cycle and a smaller seasonal change (Table 1). The difference between

rectal temperature and tympanic temperature increased with rising rectal temperature (Fig. 6). The coefficient of regression was 1.28.

Respiratory frequency. Respiratory frequency was significantly correlated with skin temperature only in both seasons ($r = 0.75$, $P < 0.01$). The relationship between mean skin temperature and respiratory frequency was linear (Fig. 7).

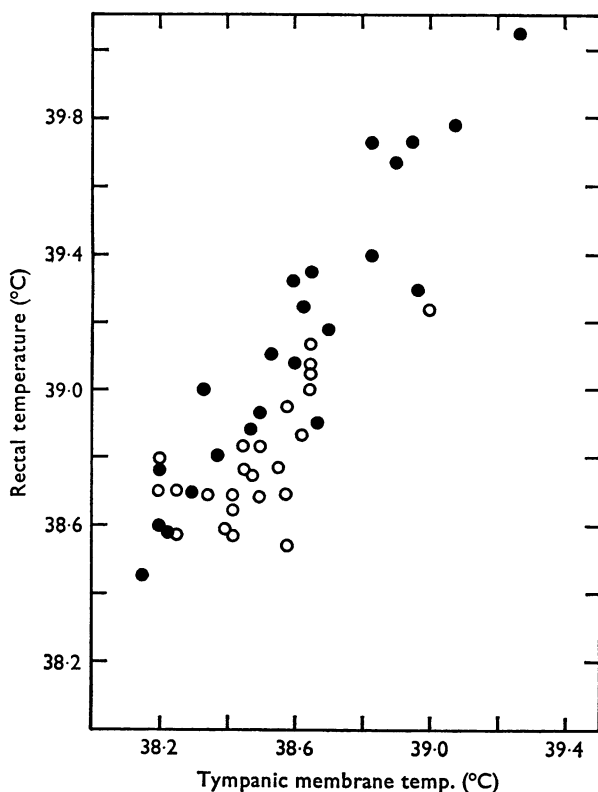


Fig. 6. Scatter of group means of rectal temperature plotted *versus* tympanic membrane temperature at each measurement period in the two seasons. Legend as in Fig. 1.

DISCUSSION

The absence of a nycthemeral cycle in the rate of heat production is supported by earlier evidence (Berman, 1968). This suggests that the high producing dairy cow is not able to cycle its internal heat production to a peak coinciding with the cooler part of the day. The ruminants differ from the monogastric animals in that the heat originating from the bacterial fermentation of feed in the fore-stomachs is an important component of the internal heat load. This fermentation is a continuous process not subject to the normal systems regulating metabolic rate.

Rectal temperature was more sensitive to changes in the ambient heat load than was tympanic temperature. This differs from the situation in man in which, at similar rates of heat storage in the body, the rectal-to-tympanic gradient was constant (Minard & Copman, 1963).

A probable reason for this discrepancy can be found in the exchange of heat between rumen and body. Feeding creates a marked and prolonged rumen-to-rectal temperature gradient (Brody, Dale & Stewart,

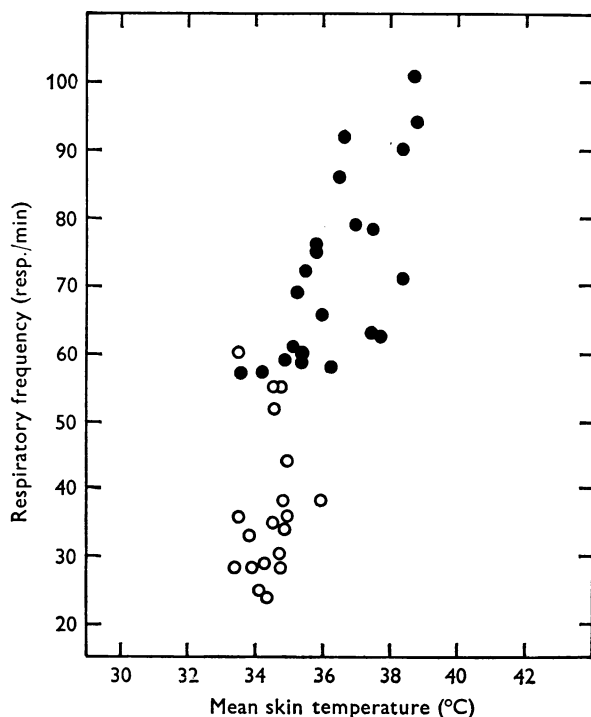


Fig. 7. Scatter of group means of respiratory frequency plotted *versus* mean skin temperature at each measurement period in the two seasons. Legend as in Fig. 1.

1955). On rumen heating or cooling both the rate of temperature change and the total change are larger for rectal temperatures than for either intrajugular or intracarotid temperatures. Intravascular temperatures also returned to normal within one third of the time required for rectal temperatures to return to the normal values (Mendel & Raghavan, 1966). These findings indicate that in the ruminant the proximity of the rectum to a large mass which has a low rate of heat exchange with the rest of the body may well create a situation different from that of the monogastric animal.

The definition of permitted thermolability needs clarification. It can mean variations in temperature of body regions and organs which have little thermoregulatory afferent output; in this case the variations in temperature would be of thermoregulatory interest mostly when suggesting ability to maintain normal organ function in either hyperthermal or hypothermal states.

Permitted thermolability may alternatively mean variations in temperature of thermosensitive sites, without resulting in the initiation of thermoregulatory reactions. Alterations in hypothalamic temperature do occur as spontaneous fluctuations (Forster & Ferguson, 1952), are also caused by postural changes (Fusco, 1963) and by emotional arousal (Delgado & Hanai, 1966). The sight of feed repeatedly induced similar elevations in the tympanic membrane temperature in cattle (A. Berman & J. Zamsky, unpublished observations). These did not affect thermoregulatory functions, although they were in most cases of the same magnitude as deviations which are effective regulatory signals. Similar variations in temperature were demonstrated in other brain regions following similar stimuli (Delgado & Hanai, 1966). It seems, therefore, that a limited inherent thermolability of the central thermosensitive structure is the rule rather than the outstanding case. Unfortunately, no information is available on the nycthemeral changes in hypothalamic temperature to make possible their comparison with the above-mentioned variations.

In the pooled data of this experiment respiratory frequency, K_{rs} and sweating rate were dependent on skin temperature only. In the summer data, however, K_{rs} , respiratory frequency and the heat production were significantly correlated with tympanic temperature. The small increase in mean tympanic temperature from winter to summer does not appear consistent with the suggestion (Findlay & Ingram, 1961; Ingram & Whittow, 1962) that hypothalamic temperature does affect thermoregulation in the cattle only when rising above 40.5° C. It seems more plausible that the effect of tympanic temperature on K_{rs} , heat production and respiratory frequency in the summer was associated with the twofold increase in the nycthemeral fluctuation in tympanic temperature in this season as compared to the winter.

The 0.4° C nycthemeral fluctuation in tympanic temperature in the winter is thus likely to represent an approximation of the permitted thermolability of the central thermosensors as defined by the type of animals and the climatic conditions in these observations.

Within this range, thermoregulatory responses seem to be dependent on peripheral stimuli; the threshold temperatures might be subjected to seasonal changes (Berman, 1968). Peripheral stimuli were predominant in the control of sweating rates in cattle, irrespective of tympanic tempera-

ture. Such stimuli are effective in the control of sweating in man, during transient thermal states (Wurster, McCook & Randall, 1966). This might be true in cattle also only in the transient conditions of the natural climate, as hypothalamic heating was found to activate sweating (Ingram, McLean & Whittow, 1963).

The whole-hearted co-operation of the Yotvta dairymen in providing their high-producing animals for these observations and their continuous help throughout the experimental periods are much appreciated. The co-operation of Dr M. Morag (Arid Zone Research Institute, Beer Sheva) and the assistance of Mr M. G. Granit, Mr Y. Givoni, Mr J. Samsky and Mr M. Forman in carrying out these observations, as well as the skilful processing of the data by Mrs J. Garber, are gratefully acknowledged.

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